

DEVELOPMENT OF EARTHQUAKE GROUND SHAKING MAPS FOR THE YELLOWSTONE-JACKSON HOLE-STAR VALLEY, WYOMING CORRIDOR

USGS Award Number 05HQGR0026

Bonnie J. Pickering White and Robert B. Smith (co-PI)
Department of Geology and Geophysics
University of Utah
135 South 1460 East, Room 719
Salt Lake City, UT 84112
Phone: (801) 581-7129
rbsmith@mines.utah.edu

Ivan Wong (PI)
Seismic Hazards Group
URS Corporation
1333 Broadway, Suite 800
Oakland, CA 94612
Phone: (510) 874-3014
Fax: (510) 874-3268
ivan_wong@urscorp.com

PROGRESS REPORT 1 December 2004 to 30 November 2005

The Yellowstone-Jackson Hole-Star Valley corridor is located within the seismically and tectonically active Intermountain Seismic Belt in westernmost Wyoming and eastern Idaho. The corridor has the highest seismic hazard in the Intermountain U.S. based on the U.S. Geological Survey's National Hazard Maps. The region contains the heavily visited Yellowstone and Teton National Parks and the rapidly growing areas of Jackson Hole and Star Valley. Although there has only been one large earthquake in this region in historical times (1959 **M** 7.5 Hebgen Lake), abundant geologic evidence exists for the past occurrence of surface-faulting earthquakes of **M** 7 or greater. In addition, background seismicity not associated with known faults and whose maximum magnitude is about **M** 6½ is relatively abundant within this portion of the Intermountain Seismic Belt and must be considered in seismic hazard evaluations.

A Project Team of URS Corporation, the University of Utah, the U.S. Geological Survey (USGS), the Wyoming State Geological Survey, and Pacific Engineering & Analysis has proposed to develop a series of 12 deterministic earthquake scenario and probabilistic ground shaking maps for the Yellowstone-Jackson Hole-Star Valley corridor. Ground motions will be estimated based on the most up-to-date information on seismic sources, crustal attenuation and near-surface geology. Given the location of the corridor adjacent to major faults such as the Teton and Grand Valley faults, seismic hazard evaluations need to not only consider the hazards from numerous seismic sources, but also address the near-source effects on ground motions such as hanging wall and rupture directivity effects, as well as soil amplification effects.

Scope of Work

In December 2004, URS and the University of Utah (UU) received partial funding to support the analysis of the Jackson Lake seismographic data. The following discussion describes the scope of this task. The work was performed by Mrs. Bonnie Pickering White, a graduate student in the Department of Geology and Geophysics at the UU. She was supervised by Dr. Robert Smith.

The U.S. Bureau of Reclamation (USBR) released their 18-year (1986-2002) catalog of earthquakes recorded by the Jackson Lake Seismic Network that was terminated in 2002. Earthquakes in the study area were recorded on up to 20 short-period and broadband seismographs located in Jackson Hole, a deep alluvial filled valley bounded on the west by the Teton fault. These data include waveforms and picked first-arrivals of 8,000+ events recorded from 1986 to 2002 of $0.5 < M < 4.7$. In this task, the P- and S-wave arrival time data were analyzed to create a new catalog of precisely located earthquakes using a new nonlinear probabilistic method and P-wave tomography-determined 3-D velocity models. Amplitudes and coda decay were evaluated to provide information on magnitude scaling.

The earthquake data were re-evaluated by manually re-picking and analyzing about 10% of events, as well as all events of $M > 2.5$ using the UU seismographic station's online seismic analysis tools (routinely used for analysis of the Utah and Yellowstone network data) and SAC. This provided estimates of the uncertainty in the automated picking process and the capability to evaluate waveforms for basin or other unusual propagation properties. Hypocenters were then relocated using a nonlinear, probabilistic solution to the earthquake location problem with uncertainties allowing a better and more reliable classification of earthquake locations. Double-difference hypocenter solutions were also computed and compared with the nonlinear locations. The improved hypocenters were used to evaluate the location and geometry of the Teton fault that has been hypothesized to extend basin-ward as a steep planar fault, to a shallow dipping to listric fault extending beneath the populated centers of the valley.

Focal mechanisms were inverted to determine the stress field orientation. These data were compared with fault-stress loading models of the Teton fault and their interaction with adjacent seismogenic structures such as the Hoback fault, the nearest fault to the town of Jackson, and several large right-stepping normal faults of the adjacent Yellowstone system. The stress field and stressing rates can then be compared with strain rate data acquired by a 10-station GPS network, acquired since 1989 by the UU, and precision leveling across the Teton fault, acquired by the University of California, Santa Barbara and the UU since 1991. These data may help refine the location and geometry of the Teton fault, provide fault-stress loading conditions, and provide key input into the probabilistic seismic hazard analysis. The latter is critical because of the seismic quiescence of the Teton fault compared to its late Quaternary fault loading rate, determined from trenching at 1-2 mm/yr and horizontal fault loading rates determined by GPS of ~2-3 mm/yr.

Results

General Accomplishments – During the reporting period, the UU focused primarily on developing a refined hypocenter location catalog of the Teton region using a non-linear probabilistic method and tomography-determined 3-D P-wave velocity models. The Teton region is shown in Figure 1 and extends from southern Yellowstone down to the Star Valley, Wyoming, and across from Driggs, Idaho, to the eastern Gros Ventre Range. The data collection

and analysis were completed along with the initial cross-correlation of the entire data set and a finalized minimum 1-D velocity model.

Focal mechanisms were determined from the highest quality 1-D relocated events and inverted to determine regional stress field orientations that were then compared to geodetic deformation rates to understand the regional and local stresses on the Teton fault. 3-D velocity models are currently being finalized for the Teton region and will be used to relocate all recorded earthquakes using the nonlinear, probabilistic approach.

Problems Encountered – We received the USBR Teton Seismic Network data files in late January 2005. The main problem encountered was converting the earthquake waveform files from an old data format to a newer version that we use to run our programs. This conversion took two months to complete.

Data Collection and Re-Analysis of Events – The USBR's Teton earthquake data set for P-wave data was analyzed by re-evaluating about 10% of events, as well as all events of $M > 2.5$ per year events using our online seismic analysis tools and SAC. There were no events that needed to be re-picked manually since the USBR had manually gone back to correct any picks generated from their automated algorithm. We determined estimates of the uncertainty in the automated picking process by comparing the USBR's manual uncertainty estimates with our own that we currently use in our Yellowstone and Utah networks. The uncertainties and weighted picking schemes generated by the USBR are similar to the same uncertainty and weights the UU uses for our networks.

Cross-Correlation of Waveforms – Cross-correlation on the original USBR's seismic waveform data was also done to aid in improving absolute picks for earthquake events that have similar waveforms. A code developed by Charlotte Rowe (2000) enabled us to cross-correlate all the events in the entire data set with one another. The Teton region earthquakes failed to produce significant clusters of similar waveforms inside the Jackson Lake Network as a whole data set. Therefore we were not able to improve very many picks for earthquakes with similar waveforms.

We will be examining clusters of spatially grouped hypocenter locations once the final 3-D tomography is complete and a new relocated catalog is finished. Hopefully with the relocated events more earthquake clusters will be spatially defined where we will be able to analyze individual clusters in more detail.

1-D P-Wave Velocity Model – From the analysis and correlated initial P wave picks which we examined and found to be very accurate, we were able to relocate all the events using a minimum 1-D velocity model we created for the Teton region using the program VELEST. VELEST iteratively solves the coupled hypocenter-velocity problem by simultaneously inverting for hypocentral parameters, seismic velocities, and station corrections. After using a nonlinear relocation method, we were able to reduce the hypocenter RMS values by 32% thereby decreasing the average horizontal location error of the event from about 4.5 km to about 3 km.

Figure 1a shows the relocated hypocenter distribution of Teton region earthquakes. These data show a generally diffused pattern of epicenters across the southern Teton region while a seismic gap of events occupies the northern part of the fault zone. The cross sections in Figure 1b suggest that events do not correlate with the projection of the Teton fault at depth. However we

are seeing some pattern to the west of the fault in which the earthquakes are creating a curving pattern possibly outlining the root of the Teton Range suggesting the interaction of the normal fault system with east-west trending Laramide thrusts, perhaps as reactivated faults. We will examine this aspect of the seismic pattern and focal depths when the complete 3-D velocity model is finalized.

Focal Mechanisms and Regional Stress Field – Using the 1-D relocated earthquake events, 600 high quality events were chosen to generate focal mechanisms. The high quality events contained at least eight 1st-motion picks, a gap less than 180 degrees, an RMS error of less than 0.5 sec, and a distance to closest station ratio of less than 1.5 times the focal depth.

Note that in Figure 2, normal faulting predominates in the Teton region, although strike-slip events and oblique strike-slip events are also occurring throughout the region. Using the high quality events, we have grouped the focal mechanisms by their geographic location and T-axis orientations (Figure 2).

We have separated the focal-mechanisms into five regions of relatively homogenous strain representing the northern part of the Teton fault (A), the Teton mountain block (B), the Jackson Hole valley block (C), and the two sections of the southern Teton fault region (D and E) (Figure 2). Most of the areas display the minimum principal stress-axis direction in an east-west direction where as the northern Teton fault shows a northeast-southwest extensional direction that could be influenced by the stress field of the Yellowstone volcanic system. The stress-field inversion results derived using an algorithm by Abers and Gephart (2001) correlates well with the focal mechanism T-axes orientations that show extension across the Teton fault with a rotated orientation towards the northern end of the fault (Figure 2). These stress field inversion results will not change much with the 3-D tomography but focal mechanisms for all the events will be recalculated after the final catalog is complete given there will be improved take off angles from the 3-D tomography.

3-D Velocity Model – Using the minimum 1-D velocity model, an initial 3-D velocity model was generated. We performed numerous tests on the model and damping parameters in order to obtain the most probable velocity model for the Teton region. Sensitivity tests are currently being conducted to determine the resolution quality of the model. Once all tests are completed, we will have a finalized 3-D velocity model that represents the velocity distributions of the sediment structure at depth in the greater Teton area.

Figure 3 shows our latest 3-D velocity model for the Teton region and we can see the low velocity zones indicating the sediment basins in the Jackson Hole valley and the town of Jackson at depths down to 5 km. The low velocity zones continue to depths of 10 km and one interesting observation is that these zones at 10 km depth seem to be correlating with the Cache Creek thrusting zone. Once the 3-D velocity model is finalized, we will relocate all 8,000+ events using a nonlinear relocation program using this 3-D model completing the relocated earthquake catalog for the Teton region.

Magnitude Calibration – Amplitudes and coda decay are currently being evaluated to provide information on magnitude scaling. Comparing the local magnitude scale determined by the USBR for the Jackson Lake network, our initial examination shows that the USBR magnitudes closely correlate, using 135 Teton coda magnitudes, to the scale employed by the UU Seismograph Station (Figure 4). The trend of the different magnitude scales from the same

earthquakes displays a small average error of about a ± 0.5 magnitude difference that is typical between various networks and scaling algorithms.

Important Questions – There are several important questions that arise when discussing the Teton fault and its tectonic activity. Also, relevant to seismic hazards we must address the attenuation of ground motions in the Teton region given that it is in an extensional regime bounded by a large magmatic system, Yellowstone. We must also evaluate how the post-glacial, <14,000 years BP, fault slip rate along the Teton fault shown in Figure 5 reflects the loading rate that should be employed in probabilistic hazard assessment. Based on trenching of the southern Teton fault, the last recorded faulting event, ~1 m, along the Teton fault occurred ~4,000 years ago, with another ~7,000 year event of 1.8 m. However, from the measured total Holocene fault scarp of up to 20 m, there must have been 5 to 15 large magnitude events to account for the observed total displacement. Other ideas are that the large fault displacement events were aided by stress unloading of the glaciers in the Teton region at deglaciation time, ~14,000 years ago.

The most important question that is raised when discussing the Teton fault is why is there a seismic gap along the northern segment of the fault. The results of GPS and leveling surveys of the Teton fault suggest horizontal deformation rates up to 2 to 3 mm/yr of fault-normal compression suggesting that the fault may be locked. This stress regime may account for the seismic quiescent nature of the northern Teton fault. We will address these hypotheses during our future work.

Non-Technical Summary

Under this project, the UU revised the earthquake data in the Teton region using a new 3-D P-wave velocity model developed specifically for the area. These data will aid in the evaluation of the location and geometry of the Teton fault that has been hypothesized to extend basin-ward as a steep planar fault, to a shallow dipping to curving fault extending beneath the populated areas of Jackson Hole. Moreover the data will provide key information on the regional recurrence information that is necessary for hazard assessments. Stress orientations derived from the earthquake data will be compared with fault-stress rate models of the Teton fault and their interactions with adjacent structures such as the Hoback fault, the nearest fault to the town of Jackson, and several large faults of the adjacent Yellowstone system. The stress field and stress rates will also be compared to strain rate data derived from geodetic data to help provide fault conditions and provide key input into the probabilistic earthquake hazards analysis.

Meeting Participations

Presentations on this project and related research were made at the: 1) September 2004 SESAC (Scientific Earthquake Studies Advisory Committee of the USGS) meeting; 2) July 2005 National Park Service-Geologic Scope Meeting; 3) October 2005 Grand Teton National Park Foundation Forum; and 4) October 2005 Fall Meeting of the Geological Society of America.

Collaborative Efforts

We are collaborating with Chris Wood, USBR; Dan O'Connell, USBR; Stephan Husen, Swiss Seismological Service; Lisa Block, USBR; Christine Puskas, University of Utah; Wu-Long Chan, University of Utah; and Greg Waite, USGS.

Publications and Abstracts

- White, B.J.P., Smith, R.B., Husen, S., Puskas, C.M., Wong, I.G., and Sylvester, A., 2005, Seismotectonics of the Teton fault from a revised earthquake catalog and stress-field inversion (abs.), EOS Transactions, American Geophysical Union (CD ROM).
- White, B.J.P., Smith, R.B., Puskas, C.M., Wong, I.G., and Sylvester, A., 2005, Seismotectonics and stress field of the Teton fault and interactions with the Yellowstone volcanic plateau from earthquake and fault-slip data (abs.), Abstracts with Programs, Geological Society of America, v. 37, p. 60.

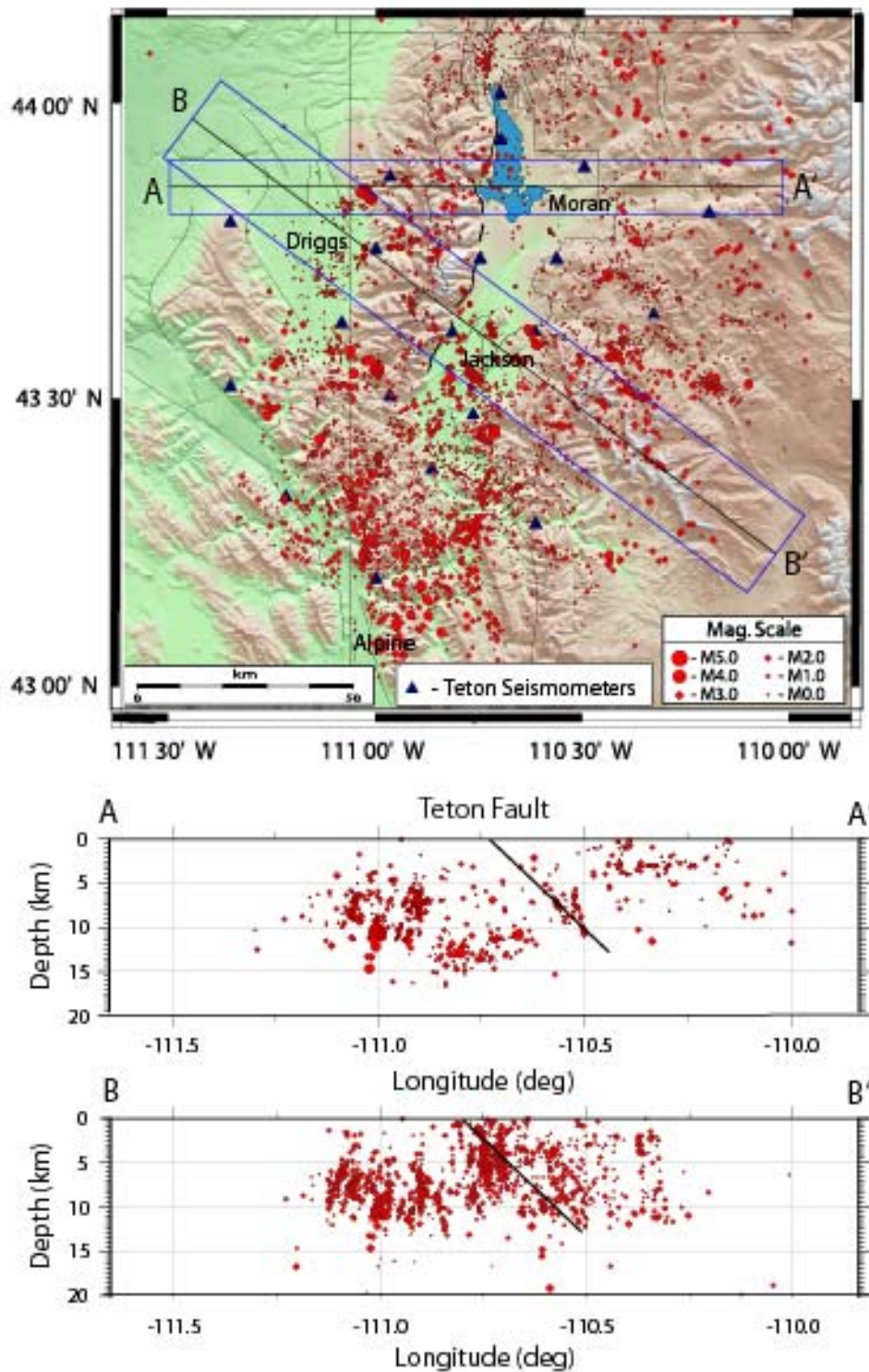


Figure 1. Seismicity map of the Teton region earthquakes relocated using the minimum 1-D velocity model. Grand Teton National Park is outlined in black. Seismicity cross-sections show the down-dip projection of the Teton fault.

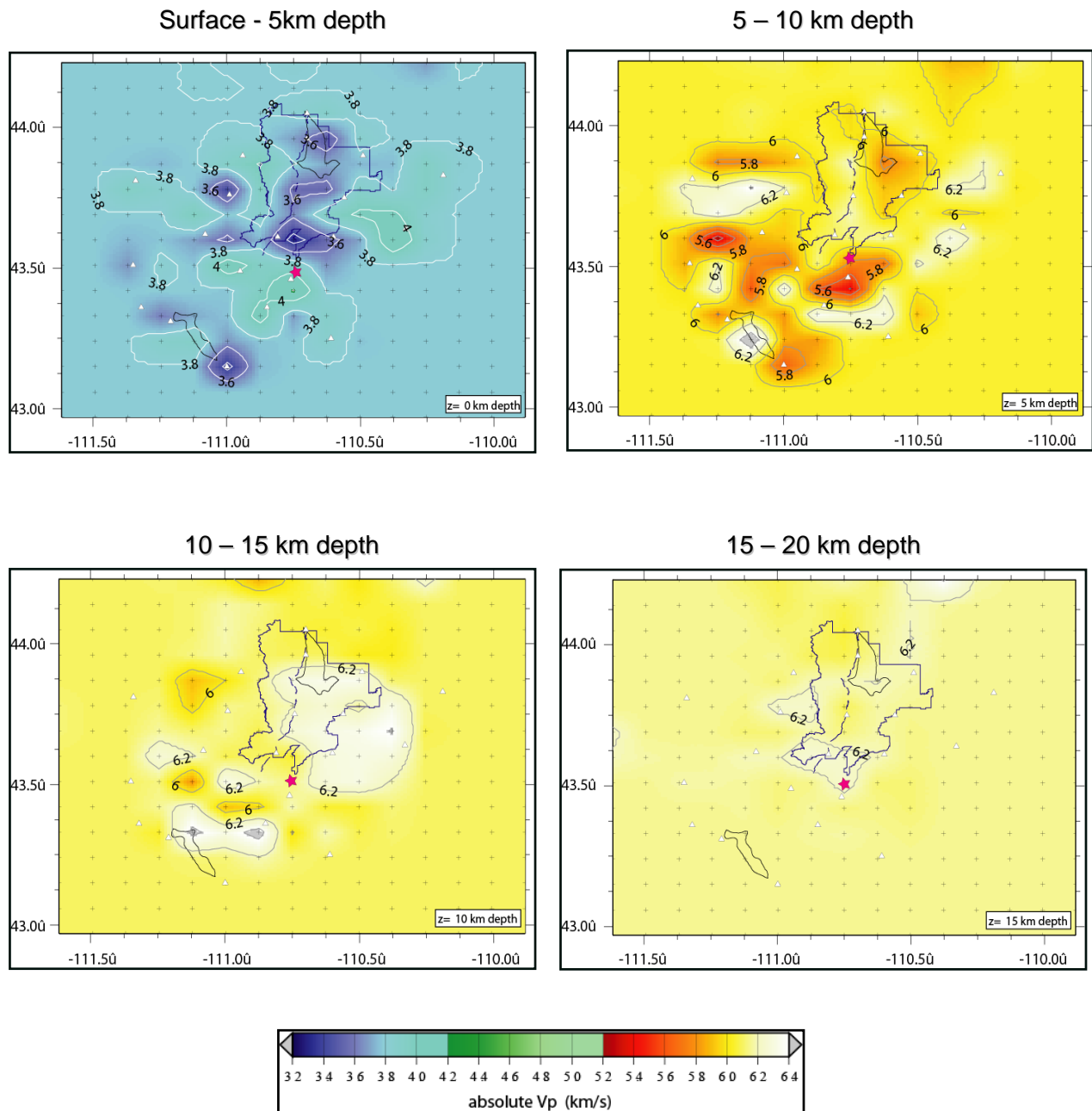


Figure 3. Preliminary 3-D P-wave velocity model for the Teton region. The black outline is the Grand Teton National Park boundary and the Teton fault. Jackson Lake is also outlined in black. The pink star is the location of Jackson, WY.

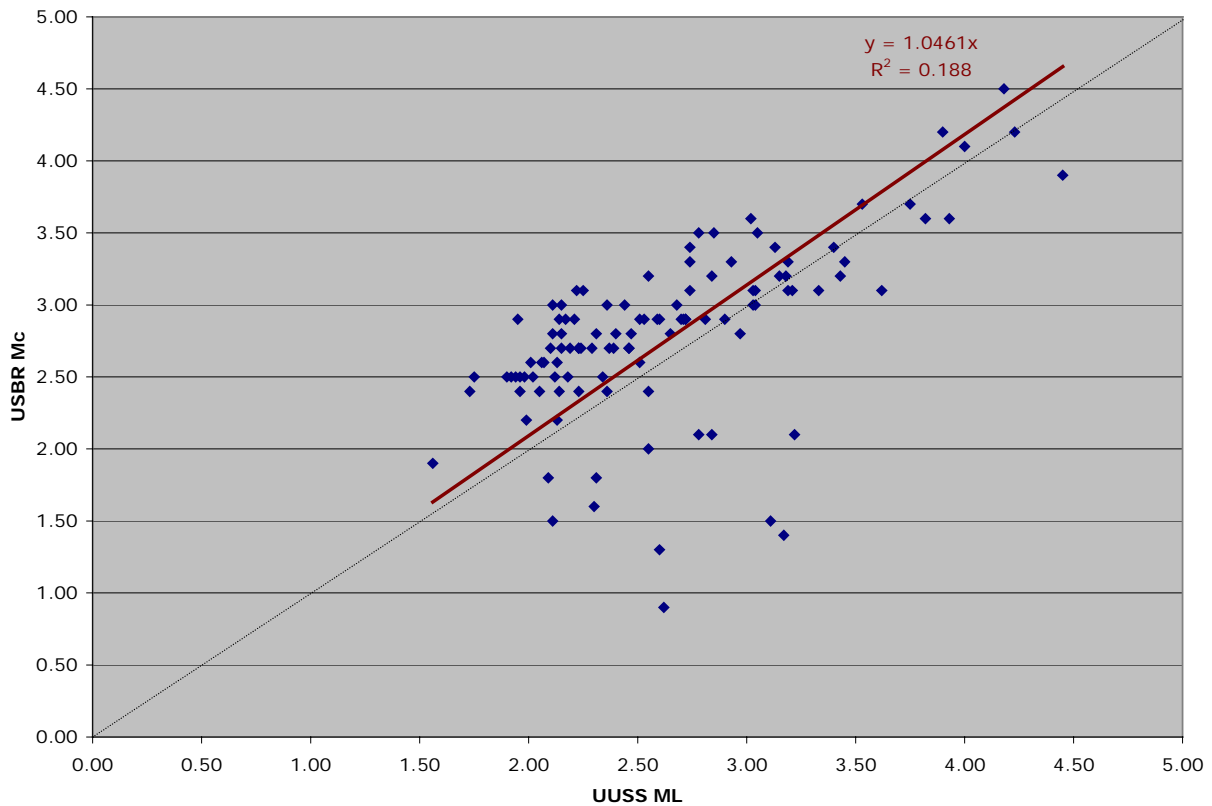


Figure 4. Comparison of the U.S. Bureau of Reclamation's coda magnitude scale for the Jackson Lake seismic network with the University of Utah Seismograph Station's local magnitude scale. These data are for 135 earthquakes recorded both by the USBR's Jackson Lake Seismic Network and by the UUSS' Yellowstone and Utah seismic network. The dotted black line shows an exact correlation between the two magnitude scales. The red line shows the best-fit comparison for all the 135 events.

